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The cumulative impacts of repeated heavy rainfall, flooding and altered water quality on the high-latitude coral reefs of Hervey Bay, Queensland, Australia

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ABSTRACT

Terrestrial runoff and flooding have resulted in major impacts on coral communities worldwide, but we lack detailed understanding of flood plume conditions and their ecological effects. Over the course of repeated flooding between 2010 and 2013, we measured coral cover and water quality on the high-latitude coral reefs of Hervey Bay, Queensland, Australia. In 2013, salinity, total suspended solids, total nitrogen and total phosphorus were altered for up to six months post-flooding. Submarine groundwater caused hypo-saline conditions for a further four months. Despite the greater magnitude of flooding in 2013, declines in coral abundance (~28%) from these floods were lower than the 2011 flood (~40%), which occurred immediately after a decade of severe drought. There was an overall cumulative decrease of coral by ~56% from 2010 to 2013. Our study highlights the need for local scale monitoring and research to facilitate informed management and conservation of catchments and marine environments.

1. Introduction

Flooding is a natural occurrence which can be an important source of sediment and nutrients to a variety of downstream riverine, estuarine and marine environments (Furnas, 2003). However, when catchments are modified or floodwaters become increasingly large and more frequent, the benefits of flooding can be overridden by the excessive transport of freshwater, nutrients, sediment and pollution. The effects of excessive flooding on downstream environments have been documented for many years but we are only just beginning to understand how far-reaching and long lasting the impacts can be. While many studies have shown, for example, localised negative impacts of flooding on the marine environment, such as coral reefs (Butler et al., 2013) or sea grasses (Campbell and McKenzie, 2004), the transport of sediment and nutrients may also have long lasting effects over hundreds or thousands of kilometres (Brodie et al., 2012a).

There have been many reports of flooding impacts on coral reefs (Lovell, 1989; Ayling and Ayling, 1998; Butler et al., 2013; Jones and Berkelmans, 2014). Mortality can rapidly occur when corals experience extreme hyposalinity (Jokiel et al., 1993) or heavy sedimentation (Riegl, 1995), particularly when combined with high nutrient levels (Fabricius and Wolanski, 2000; Fabricius et al., 2003). Long lasting negative impacts to corals and coral communities may arise through the energetic costs of persisting through degraded water quality that occurs during, and persists after, flooding. Hyposalinity causes physiological and osmotic stress (Fabricius, 2005; Berkelmans et al., 2012) while elevated sedimentation and turbidity reduce photosynthesis, which reduces energy reserves (Philipp and Fabricius, 2003; Erftemeijer et al., 2012). Prolonged exposure of corals to sedimentation and nutrients can result in increased morbidity and bleaching (Weber et al., 2012; D'Angelo and Wiedenmann, 2014; Pollock et al., 2014), while the need for repeated removal of sediment comes at great energetic cost (Stafford-Smith and Ormond, 1992; Weber et al., 2006).

Although the potential negative effects of flood plumes on corals are well understood, rarely are measurements made on reefs during the course of flooding to understand the spatial and temporal variation in salinity, sediment, turbidity and nutrients. Such variations may be significant. For example, during the 2011 floods in Hervey Bay, Queensland, Australia coral mortality varied with proximity to the mainland as a result of wind direction, currents and flood plume pathway, but not with proximity to the adjacent

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Mary River (Butler et al., 2013), yet exposure to this river is an important factor in the distribution of coral communities in Hervey Bay (Zann, 2012). While the adverse effects of flood transported hyposaline waters, sediment and nutrients are understood generally, much less is known of the day to day variability in flood waters conditions and how the exposure to this translates into mortality and post-flood coral health. Exposure to these stressors and pollutants can last from hours to months and levels of mortality will depend on the magnitudes and combinations of these stressors (Fabricius, 2005; Berkelmans et al., 2012). In non-flood situations, salinities from 26 to 30 ppt may cause mortality after as little as one day of exposure (Berkelmans et al., 2012). Elevated turbidity (>30 NTU) and sedimentation may take weeks to significantly impact corals (Fabricius, 2005; Weber et al., 2006), however, when sedimentation is combined with elevated nutrients, mortality may take only a matter of days (Fabricius et al., 2003; Weber et al., 2012).

Although water quality monitoring is carried out worldwide, the general aim of these programs is to capture ambient levels of water quality parameters or target the sources of altered water conditions over broad time frames. These time scales tend to be inappropriate for capturing acute short term events such as flooding, which require a more targeted, intensive sampling regime over hours, days or weeks at the onset of flooding, which itself is unpredictable. Generalised large scale monitoring, while appropriate for measuring regional conditions, is inappropriate for understanding water conditions in particular habitats at specific locations. The actual content of floodwaters and their duration in the water column are important for understanding the true exposure of an organism to these altered conditions. In eastern Australia, for example, as a result of the ephemeral nature of the river systems, floodwaters are the primary means of sediment and nutrient transport to downstream areas (Furnas, 2003; Wooldridge et al., 2006). Knowledge of the magnitude of floodwaters and the conditions within them is thought to provide great insight into the health of the catchment from which the floodwaters were derived (Wallace et al., 2009; Kroon et al., 2011; Kroon, 2012), but these data are rarely collected. Through the measurement of parameters such as suspended solids and nutrients, we can assess impacts (e.g. erosion or over-use of fertilisers) within a catchment and then specifically measure their influences through future monitoring to determine the effectiveness of catchment management (Kroon, 2012).

When conducted at local scales, water quality studies can inform local environmental management. For example, such studies could be used to expand on the local relevance of the Environmental Protection Policies (DERM, 2010a,b,c). These regional guidelines are derived from the framework of the Australia New Zealand Environment and Conservation Council (ANZECC) guidelines (ANZECC, 2000) which recommends refining local guidelines to ensure environmentally safe ambient levels of water quality over the long term. However, these guidelines do not account for short term pulses of poor water quality, such as flooding, even though they can cause major, potentially long term, impacts to local marine ecosystems (Preen and Marsh, 1995; Preen et al., 1995; Butler et al., 2013). Local scale water quality studies can also provide further information about the local marine environment. For example, many coastal areas of eastern Australia (e.g. Hervey Bay) have extensive groundwater dependent terrestrial habitats (see atlas: (BOM, 2015)), including extensive areas of seagrass, which are known to, at times, depend upon submarine groundwater discharge (SGD) (Johannes and Hearn, 1985), but little is known about the volume and content of the groundwater discharge itself and any potential for impacts on other local habitats, such as coral reefs. Elsewhere, SGD is considered to be a significant source of hyposaline water, nutrients (Moore, 2010) and pollutants (Costa et al., 2008; Burnett et al., 2009) to the marine environment, especially during periods of flooding (Santos et al., 2013).

In January 2011, intense flooding occurred along the east coast of Queensland, Australia (Fig. 1). In January 2013 and then again in February 2013 this same region experienced another two episodes of intense rainfall, including a severe storm from a passing tropical low pressure system (ex-cyclone Oswald). The subsequent downstream transport of sediment and freshwater from the highly modified Mary River resulted in flood plumes that travelled over seventy kilometres from the mainland into Hervey Bay (Fig. 1) and along the coast to the north (Fig. 2). This study follows on from initial work which assessed the impacts of the 2011 Mary River flood on the marginal, high-latitude coral reefs of Hervey Bay (Butler et al., 2013). Here we examine the effects of repeated flooding on the coral communities of Hervey Bay. We investigate changes in water quality over the course of the 2013 flood plumes and assess changes in hard and soft coral abundance relative to 2011 levels. Moreover, to investigate the effects of multiple flood events on the coral reefs of Hervey Bay, we compare post-flood coral abundance to pre-flooding conditions in 2010. Our study thus provides understanding of the effects of flood plume waters on water quality, on the duration and spatial variability of flood conditions and on the impacts of repeated flooding from the highly anthropogenically modified Mary River catchment on the coral reefs of Hervey Bay.

2. Materials and methods

2.1. The study area

Hervey Bay (25.3°S, 152.8°E) is situated at the northern end of the Great Sandy Straits on the southern coast of Queensland, Australia (Fig. 1). Six coral reef sites were examined for this study: 4 Mile Reef, Burkitt's Reef, Pt. Vernon West, Pt. Vernon East, Pialba and Big Woody (Fig. 1). Four Mile Reef occurs at 10 m depth and all the other reefs of this study occur in 5 m depth (Highest Astronomical Tide (HAT)) and are variously located up to 70 km from either the Burnett or Mary rivers and up to 5 km from the mainland (Table 1). All reefs are protected from prevailing oceanic swell by the presence of Fraser Island, although Burkitt's and 4 Mile reefs are more exposed to wave action due to longer fetch (70 km) (Fig. 1). Hervey Bay, the reef sites and the Mary River are described in further detail by Butler et al. (2013).

2.2. Nearshore water quality monitoring

We initiated a water quality measurement program on January 29, 2013, just after the onset of the first flood of 2013, to monitor water conditions in the flood plumes through the nearshore coral reef areas of Hervey Bay. We conducted sampling every few days during the flooding but, after water conditions cleared through April, it was reduced to monthly until August. We chose the three sampling locations, Pt. Vernon West, Pt. Vernon East and Pialba (Fig. 1) because of the existence of long-term coral monitoring data for these sites and due to easy accessibility from shore by inflatable watercraft. The timing of sampling at the reefs also complemented an existing offshore monthly water quality sampling program carried out by the Queensland state government. In the nearshore reef areas, we collected three samples between 200 and 700 m from the Hervey Bay shoreline (Fig. 1). Samples were collected approximately 100 m apart and from approximately 80 cm below the surface in waters that were ~2 to 3 m depth at mid-tide. All samples were either chilled or frozen, as required for specific tests, and then sent for analysis to a local National Association of Testing Authorities (NATA) approved laboratory (Wide Bay Water,

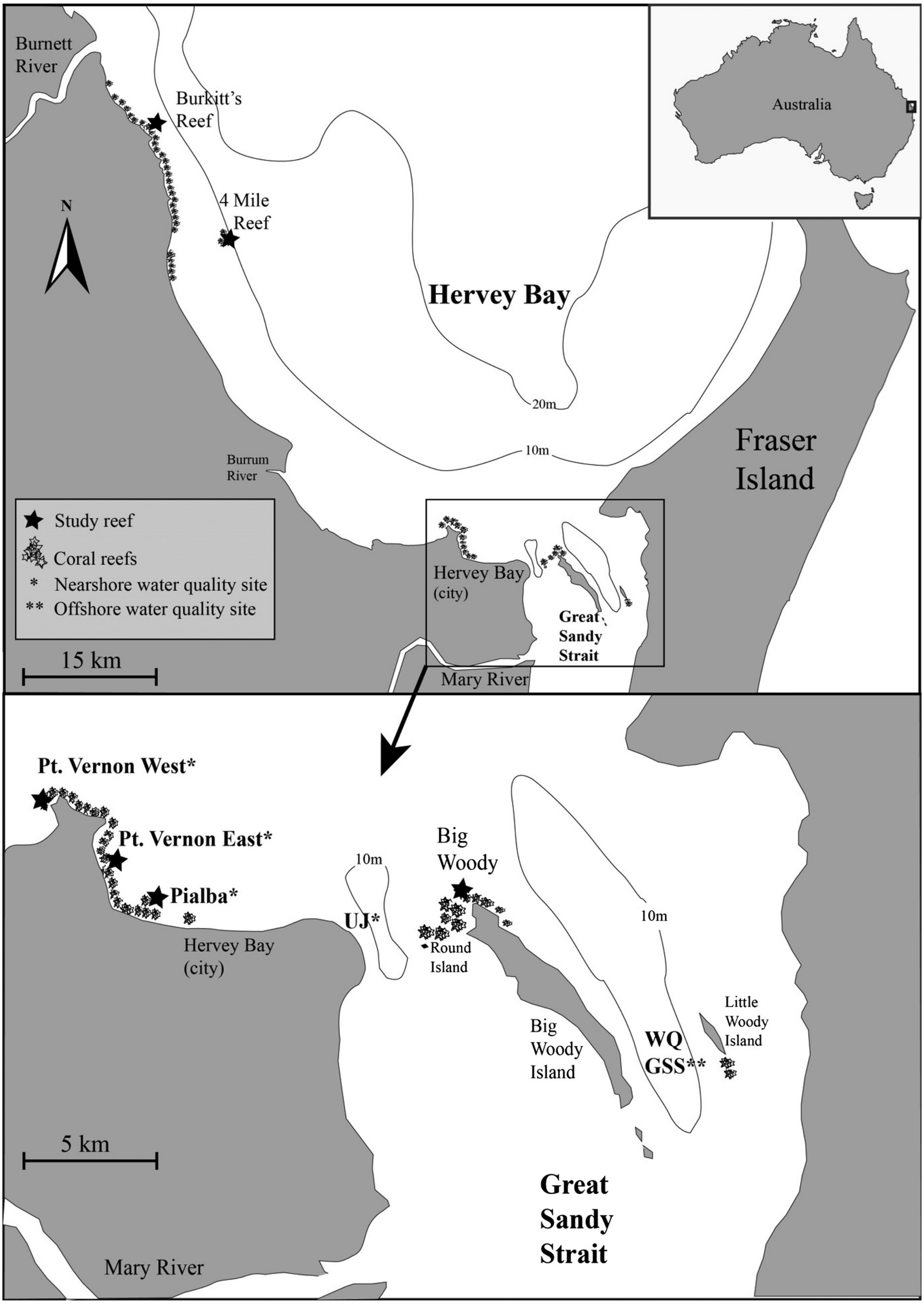

Fig. 1. Location of Mary and Burnett rivers, coral reef study sites, nearshore (*) and offshore (**) water quality sites in Hervey Bay, Queensland, Australia. WQGSS = Great Sandy Straits, government offshore water quality site, UJ = Urangan Jetty, government nearshore water quality site.

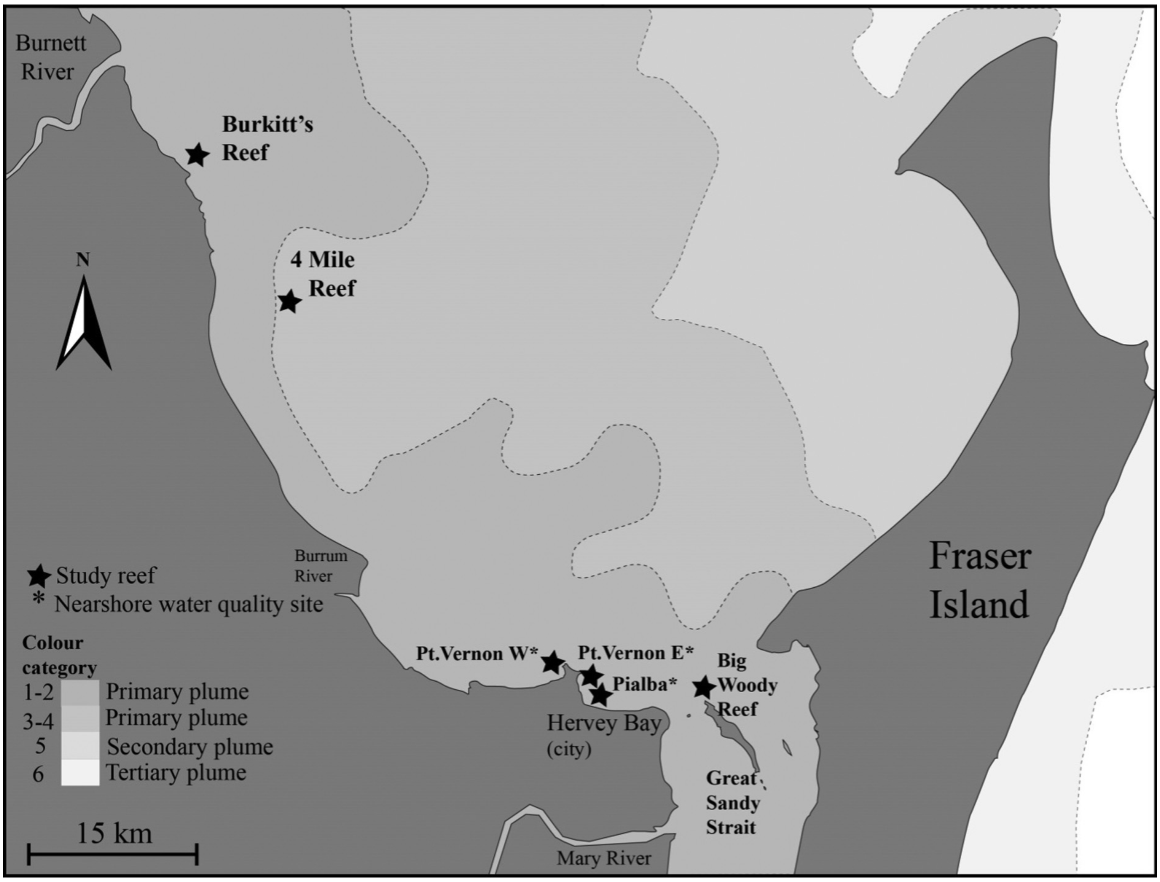

Fig. 2. Extent of first Mary River flood plume from 26 January to 2 February 2013 in Hervey Bay, Queensland, Australia characterized by remotely sensed colour classification. Darkest to lightest shading shows primary, secondary and tertiary plumes, respectively, and their numerical colour classifications (Numbered 1–6) as per methods of Alvarez-Romero et al. (2013). No shading indicates no flood plume detected remotely. Remotely sensed mapping from Da Silva et al. (2013).

Table 1
Size, depth range, distance to mainland and distance to mouth of the nearest river for the reef survey sites in Hervey Bay, Queensland, Australia.

Reef	Area (m^2)	Depth (m HAT)	Distance mainland (km)	Distance mouth nearest river (km)
Burkitt's Reef	Fringing	5	0.5	10
4 Mile Reef	20000	10	5.0	70
Pt. Vernon West	Fringing	5	0.4	30
Pt. Vernon East	Fringing	5	0.25	26
Pialba	Fringing	5	0.7	24
Big Woody	Fringing	5	4.0	18

Hervey Bay) (81 samples) or to the state government's Department of Science, Information Technology, Innovation and Arts (DSITIA) laboratory in Brisbane (108 samples). All of the samples were measured for salinity, total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP) to enable comparisons with ongoing DSITIA water quality monitoring and regional state government water quality guidelines (DERM, 2010a,c). Where a measured value was below detection, a value of half the detection limit was used for analysis. In order to understand how nutrient levels varied with suspended solids and salinity in nearshore floodwaters, we plotted the measured TN and TP values individually with measurements of salinity and suspended solids from the same water samples. We then generated linear models using Pearson correlations. The same correlation was carried out for salinity versus total suspended solids.

2.3. Offshore versus nearshore comparison of water quality data

Since 1994, DSITIA has carried out a monthly water quality monitoring program in the Hervey Bay region. For comparison with the nearshore reef sites, we collated data from one of their offshore sites, WQGSS, 12 km from the mainland in Great Sandy Strait (GSS), between Big Woody Island and Fraser Island (Fig. 1), for the same time period corresponding to the nearshore flood monitoring. Data were also collated for an additional nearshore site near the jetty at Urangan (UJ) (Fig. 1), in order to determine the salinity and turbidity through the water column during the flooding. Data from these sites are single values per depth per sample date.

2.4. Photo-transect methodology for measuring coral abundance

In order to measure changes in coral abundance as a result of flooding, photo belt transects with photo software analyses (Leujak and Ormond, 2007) were carried out on six reef locations: Big Woody, Pt. Vernon East, Pt. Vernon West, Pialba, Four Mile and Burkitt's reefs (Fig. 1). Sampling was carried out in 2010 and 2011, as per Butler et al. (2013), with subsequent photo transects and analysis carried out in 2013. At each of the reef sites, photos (~60 × 70 cm) were taken at every metre along five haphazardly placed 30 m transects. The start of each transect was at least 20 m from the nearest transect, with no overlap between transects. Using the software Coral Point Count with Excel extensions (CPCE) (Kohler and Gill, 2006), each benthic image had 15 points randomly overlaid and the taxon for each point was identified to species, where possible. These were then used to calculate benthic cover. For the purposes of this study, total abundance of hard coral and total abundance of soft corals for each transect were combined into a single total abundance coral category.

2.5. Data analyses

We created univariate permutational analyses of variance (PERMANOVA) models to compare changes in total hard and soft coral abundance between single and multiple years of flooding. We used two independent variables for reef location in an analysis of covariance: distance from the nearest river, and; distance from the high tide level on the mainland. Our previous studies in this area (Butler et al., 2013) found no significant effect of distance from the mouth of the Mary River on the degree of flooding impacts. It was found through satellite imagery, however, that in 2013 Burkitt's Reef, the most northerly of reefs, was likely affected by the southward expansion of the flood plume from the Burnett River, the next major river north (Fig. 1). These analyses use the updated river distances. We did not use water quality as a predictor for coral mortality because water quality was obtained from only three of the six reef sites.

Impacts of floods were determined by comparison of abundances between years: 2011 versus 2013 for impact of 2013 floods, and; 2010 versus 2013 for effects of overall repeated flooding. Changes in abundance from 2010 versus 2011 are already described in Butler et al. (2013). Type I sum of squares were calculated to ensure that any overall effects of time were independent of the effects of the covariates. Prior to creation of the models, the square root transformed data were subject to PERMDISP analyses to assess the homogeneity in the dispersion of the data between pre- and post-flood data sets. Where lack of homogeneity of dispersion (PERMDISP, $p < 0.05$) was found in the data set, a more conservative significance level of $p = 0.01$ was used to remove non-significant factors and generate the most parsimonious models. Statistical analyses were conducted using the software PRIMER v6 (Clarke, 1993) and the add-on package PERMANOVA (Anderson et al., 2008).

3. Results

3.1. Site variability in water quality

Salinity, TSS, TN and TP at each of the reefs were highly variable between sample days (Fig. 3a–d), though the measured values were generally most elevated after each flood event and then decreased as the flood plumes dissipated. There were some clear differences between reefs, for example, the prolonged elevated total phosphorus and suspended solids at Pt. Vernon West relative to the other reefs. One-way analysis of variance (repeated measures), however, indicated no significant differences overall among the reefs: TN ($F = 0.4292$, $p > 0.05$); TP ($F = 2.038$, $p > 0.05$); salinity ($F = 1.440$, $p > 0.05$); TSS ($F = 1.625$, $p > 0.05$). Therefore, rather than analyse each reef separately, the data for all the reefs were combined.

3.2. Salinity in the flood plumes

Water quality changes in Hervey Bay were evident immediately after the onset of stormy seas and heavy rainfall in the region. This rainfall commenced on January 27, 2013 and within days the salinity at nearshore locations in the bay had dropped to as low as 14 ppt, well below the average normal salinity of 35.6 ppt (Fig. 4a and b). Salinity rose rapidly to above 30 ppt within two weeks before again dropping to around 18 ppt after the passage of the second major rainfall event on February 27 (Fig. 4b). Again, there was a subsequent rapid rise above 30 ppt within two weeks and a steady return to near normal conditions by the end of March. Hyposaline conditions at the nearshore areas, driven by the flood plume, lasted over seven weeks.

The salinity at the offshore site WQGSS was similarly affected by the flooding and rainfall, with a minimum salinity of 17 ppt and hyposalinity lasting for approximately seven weeks. The two spikes of hyposalinity, however, were not evident (Fig. 4b). Based on the monthly water quality sampling from this offshore site, salinity was substantially lower in the 2013 floods relative to those experienced in the 2011 floods, but hyposaline conditions in 2013 lasted only half as long as the 2011 flooding (Table 2).

As is typical for flood plumes entering saline waters, where lower density freshwater remains near the surface (Furnas, 2011), salinity at UJ was found to be initially lowest in the surface waters and progressively increased with depth over time (Fig. 5a). This returned to an even salinity throughout the water column with vertical mixing and as the floodwaters dissipated in April (Fig. 5a).

3.3. Delayed episode of hyposalinity

Three to seven weeks after the return of bay waters to near normal salinity, salinity again dropped at nearshore reef locations to an average of 23 ppt and remained below 30 ppt for at least twelve weeks and below average salinity (36.5 ppt) for a total of 20 weeks (Fig. 4b). This drop in salinity was not accompanied by any rainfall in the catchment or any elevated river levels (Fig. 4a). We did not detect any change in salinity at the offshore site (Fig. 4b) nor at site UJ (Fig. 5a).

3.4. Turbidity and total suspended solids in the flood plume

At nearshore reefs, TSS increased from the onset of monitoring in January (Fig. 6a) up to a maximum value of 131 mg l^{-1}. TSS fluctuated heavily between sampling times, with median values ~10 to 40 mg l^{-1} (Fig. 6a). In total, TSS exceeded environmental guidelines (4 mg l^{-1} Hervey Bay) (DERM, 2010a) for approximately twenty-four weeks. TSS measurements at the offshore site during the flood plume were 5–8 mg l^{-1}, all below environmental guidelines for Great Sandy Strait (GSS) (DERM, 2010c). At this site, elevated turbidity appears to have been relatively short-lived (less than four weeks) and exceeded environmental guidelines (2 NTU for GSS) (DERM, 2010c) only once during the flooding.

Based on the monthly water quality sampling from the offshore site, turbidity during the 2013 floods was substantially lower than during the 2011 floods (Table 2). Elevated turbidity relative to environmental guidelines in 2011 floodwaters lasted more than three times longer than the dual floods of 2013 (Table 2). As expected for sediment behaviour in flood plumes entering saline water (Furnas, 2011), turbidity at UJ was highest in surface waters at the onset of flooding and then inverted over time as sediment settled through the water column (Fig. 5b).

3.5. Total nutrients in the flood plume

TN was elevated at nearshore reef areas from the onset of flooding and remained elevated above environmental guidelines for approximately eight weeks (Fig. 6b). Maximum levels of TN (0.762 mg l^{-1}) exceeded these guidelines by nearly seven times. Median levels were variable but typically exceeded guidelines values by two to threefold (Fig. 6b). In contrast, the peak TN

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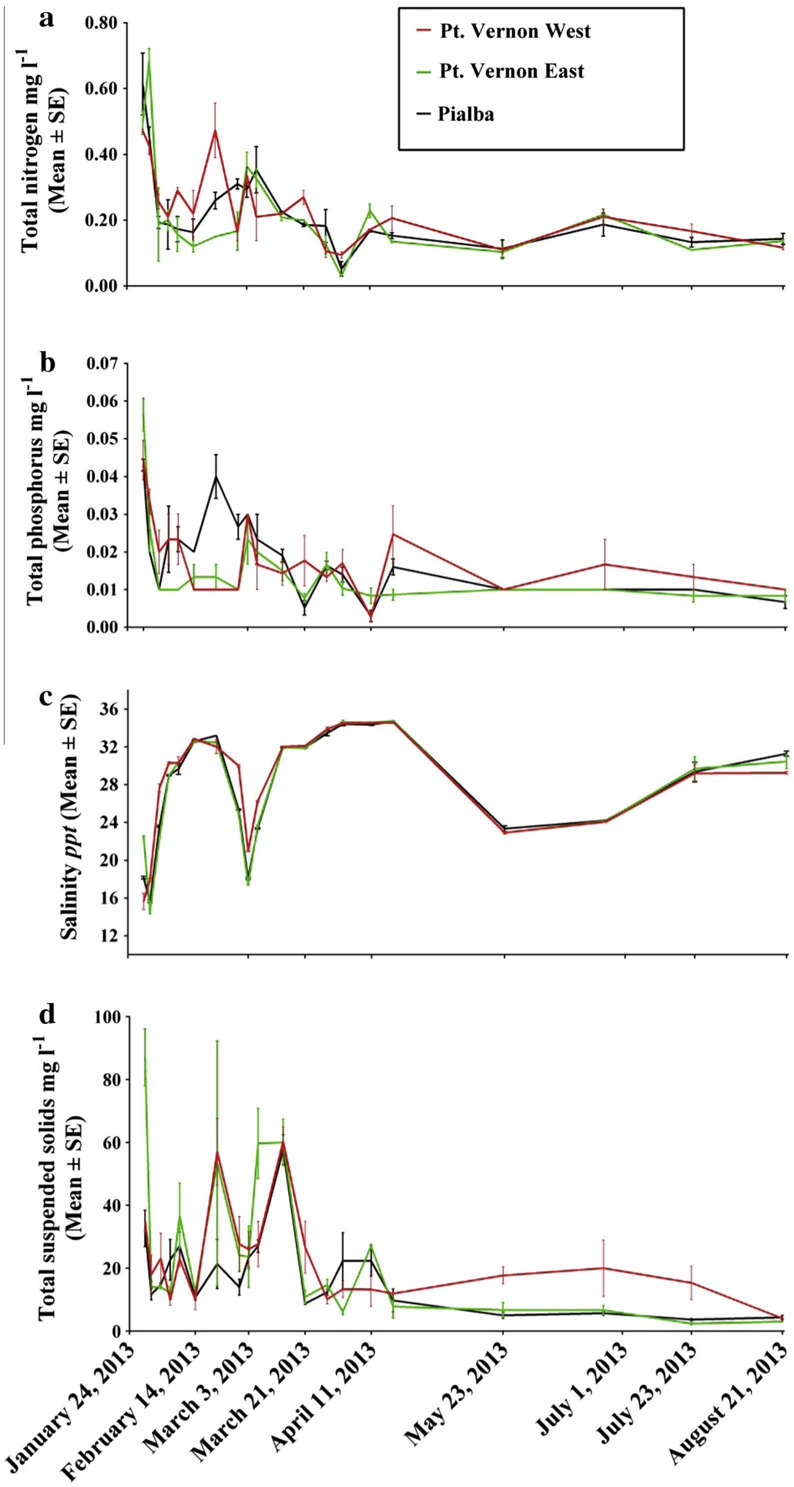

Fig. 3. Total nitrogen (TN) (a), total phosphorus (TP) (b), salinity (c) and total suspended solids (TSS) (d) measured at nearshore reef water quality sites in Hervey Bay, Queensland, Australia during and after the Mary River floods of 2013.

measurement at the offshore site (0.25 mg l^{-1}), was a third of the peak value at the nearshore locations. The duration of elevated TN at the offshore site was similar to that of the nearshore areas.

Based on the monthly water quality sampling from the offshore site, maximum TN in the 2013 floods was lower than the 2011 floods (Table 2). Duration of elevated TN in 2011 floodwaters relative to environmental guidelines was more than double that of the dual floods of 2013 (Table 2).

Total phosphorus (TP) was elevated at nearshore reef areas from the onset of flooding, though results were variable (Fig. 6c). Maximum TP (0.065 mg l) was six times the environmental guidelines and was elevated for eleven weeks in the water column

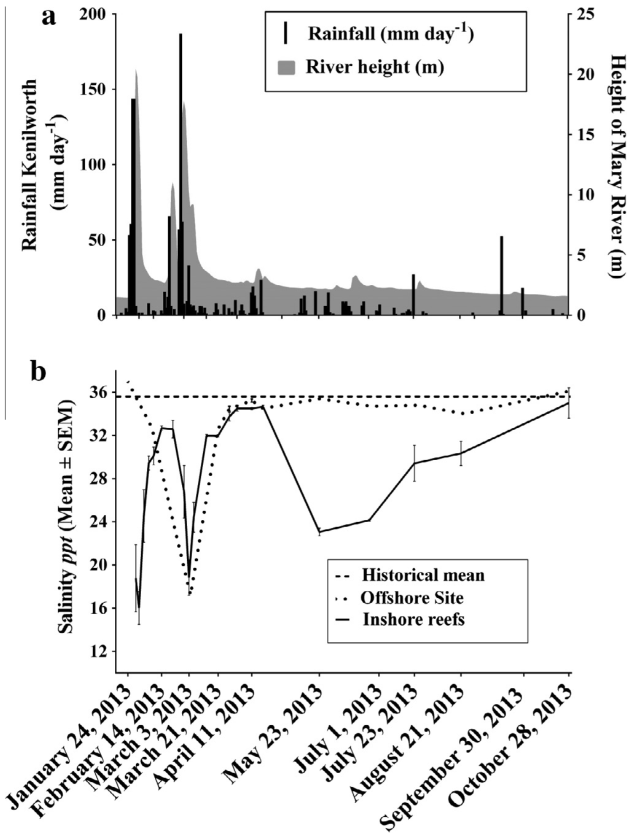

Fig. 4. Rainfall in upper Mary River catchment (Kenilworth) (a), Mary River height (at Miva station) and average salinity at the reef sites (b) in Hervey Bay, Queensland, Australia. Historical data: ©State of Queensland (Department of Science, Information Technology, Innovation and the Arts) 2013.

(Fig. 6c). At the offshore site, maximum TP reached 0.03 mg l^{-1}, half the maximum value measured nearshore. Moreover, TP at this site remained elevated for approximately six to eight weeks, which is a shorter period than at nearshore reefs.

Based on the monthly water quality sampling from the offshore site, maximum TP in the 2013 floods was greater than the 2011 floods (Table 2). Duration of elevated TP in the dual floods of 2013 floodwaters relative to environmental guidelines was similar to that of the 2011 flood (Table 2).

3.6. Nutrients versus TSS and salinity

Linear models for TN and TP in nearshore reef waters both show a highly significant positive correlation with TSS (Fig. 7a and c) indicating that elevated nutrient levels are associated with increased particulates in the water column, such as transported or resuspended sediment. In contrast, TN and TP in nearshore reef waters show a highly significant negative correlation with salinity (Fig. 7b and d), indicating that elevated nutrients are associated with hypo-saline floodwaters. While this suggests that both nutrients and sediments are being transported by the initial floodwaters, there was no significant relationship found between salinity and TSS (Fig. 7e), indicating that suspended solids during and after the floods were similar. The Pearson coefficients of determination (R^2) for all the significant correlations were generally low indicating high variability and low goodness of fit of the data to the linear models (Fig. 7a–d).

3.7. Change in total abundance of hard and soft corals after flooding

Total coral abundance declined by 28% from 2011 to 2013 (Fig. 8a), but this varied substantially among the reefs (Fig. 8b). The factors of most interest in the PERMANOVA model (Table 3) were those containing the flood elements (factor = flood), which indicate if there were significant changes in total coral abundance as a result of flooding, and the interaction of that factor with either distance from mainland (factor = distance mainland × flood) or distance from river (factor = distance river × flood). The dispersion of the total abundance data for comparing 2011 and 2013 (measuring impact of 2013 flood) was homogeneous (PERMDISP, $P > 0.05$), so a significance level of $P > 0.05$ was used to remove factors from the model. For all reefs combined, total abundance significantly declined by 28% ($P = 0.048$, Table 3) from ~29.5% in 2011 to ~21.2% in 2013 (Fig. 8a). Flood impacts were not consistent among reefs (Fig. 8b). Declines in total abundance varied from −36% (Big Woody) to −20% (Burkitt's), while abundance increased at Pt. Vernon East (+47%). Variability in flood impacts among reefs as a result of the 2013 floods was not explained by either distance from the nearest river or distance from the mainland (Table 3, Fig. 9a and b).

Not surprisingly, the overall PERMANOVA model for cumulative impact of repeated flooding over the three years (2010 versus 2013) revealed a significant overall decline in total abundance (Table 4). The dispersion of the total abundance data was homogeneous (PERMDISP, $P > 0.05$) so a significance level of $P > 0.05$ was used for model simplification. There was a significant ($P = 0.001$, Table 4) ~55.7% reduction in total abundance from ~47.9% in 2010 to ~21.2% in 2013 (Fig. 8a). Declines in total abundance occurred across all reefs, but were not consistent among the reefs. Declines in total abundance varied from −21.5% (Four Mile) to −83.8% (Pt. Vernon East) (Fig. 8b). Decrease in mortality from flood impacts was significantly correlated with distance from the nearest river (factor = distance river × flood, Table 4), whereby flood impacts decreased with increasing distance from the nearest river (Fig. 9b). In contrast with the 2011 results, there was no correlation between flood impacts and distance from the mainland (Fig. 9a, Table 4).

4. Discussion

4.1. Flooding

The improved understanding of water quality is becoming increasingly important as human population increases along

Table 2
Comparison of extremes of flood plume water quality parameters and duration below normal (salinity) or above environmental guidelines measured from offshore Great Sandy Straits (WQGSS) location for 2011 and 2013 and the nearshore reefs in 2013 of Hervey Bay, Queensland, Australia.

Parameter	WQGSS 2011	Duration (weeks)	WQGSS 2013	Duration (weeks)	Nearshore reefs 2013	Duration (weeks)
Salinity (ppt.)	31.3	<16	17.2	<8	14.1	7 + 20
Turbidity (NTU)	11	<12	3.9	<4	na	na
Total suspended solids (mg l^{-1})	na	na	11	<12	131	24
Total nitrogen (mg l^{-1})	0.360	20+	0.250	<8	0.750	8
Total phosphorus (mg l^{-1})	0.018	<8	0.030	<8	0.065	11

na = not measured.

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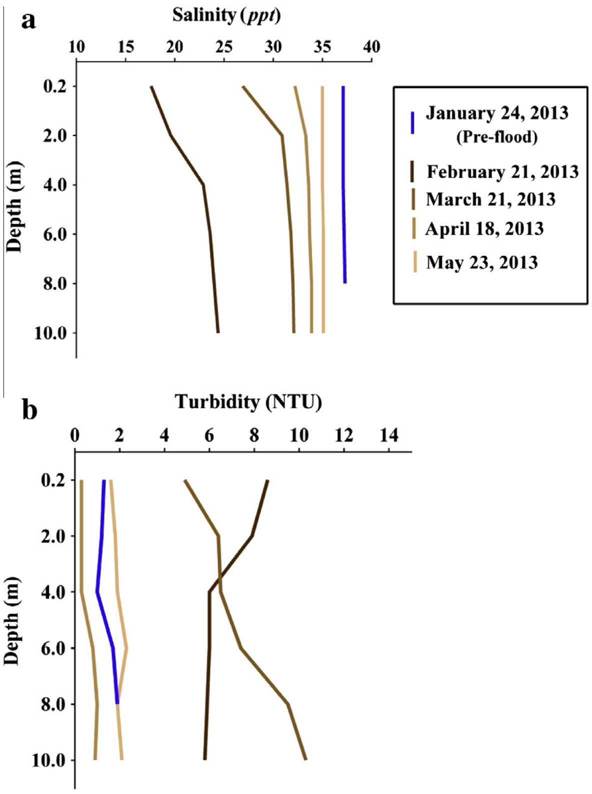

Fig. 5. Salinity (a) and turbidity (b) with water depth at the nearshore government water quality site, Urangan Jetty (UJ), Hervey Bay, Queensland, Australia before, during and after the Mary River floods of 2013. ©State of Queensland (Department of Science, Information Technology, Innovation and the Arts) 2013.

coastal zones and in river catchments. Worldwide, human activities such as deforestation (Maina et al., 2013) and dredging (Pollock et al., 2014) degrade water quality, with potential far-reaching impacts on the marine environment (Brodie et al., 2012b). In Australia, these impacts become most evident during years of high rainfall and flooding. Heavy rainfall and associated terrestrial runoff reach the marine environment in a number of ways: via direct input from rainfall, runoff from adjacent land, stormwater, long distance transport through rivers and long term input from submarine groundwater discharge (Moore, 2010).

Water quality throughout Hervey Bay was significantly altered by the combined 2013 floods (Fig. 2). Much of the bay was affected by the primary plume, the most altered of flood waters, which was characterised by remotely sensed colour classifications 1–4 (Devlin et al., 2012; Alvarez-Romero et al., 2013; Da Silva et al., 2013), with the darkest classifications (1–2) much closer to shore (Fig. 2). Sediment and nutrients were elevated well above environmental guidelines for many weeks and salinity repeatedly dropped to levels considered to be lethal to many coral species (Berkelmans et al., 2012; True, 2012). The cumulative combination of these stressors clearly impacted the coral reefs of Hervey Bay over the 2013 wet season, leading to a total decrease in coral cover of ~28% over all the sites, with a cumulative decrease of ~56% for the 2010–2013 period.

4.2. Importance of flood plume pathways and distance from the Mary River on flooding impacts

Intuitively, it would be expected that the impacts of flood waters on corals would dissipate the further a reef is located from the mouth of the source river. Butler et al. (2013) originally detected no such effect instead finding that distance from the mainland was significant, which was consistent with the nearshore path of the flood plume added onto terrestrial runoff from the adjacent land. In 2013, however, we found that the reef most distant from the Mary River, Burkitt's Reef, was probably impacted by southern extension of the record breaking 2013 flood plumes from the Burnett River, 10 km to the north of Burkitt's Reef. While it is considered likely from anecdotal evidence that southward extension also occurred in 2011, re-analysis of the 2011 data found no changes to the 2010 versus 2011 models. However, our new analysis of the overall repeated effects of flooding reveals that proximity to mainland does not significantly affect mortality, whereas proximity to nearest river does. The combined significance of both distance from shore and distance from the rivers would be expected given that the flood plumes emanate from river mouths, but are then variably pushed towards the mainland by circulation,

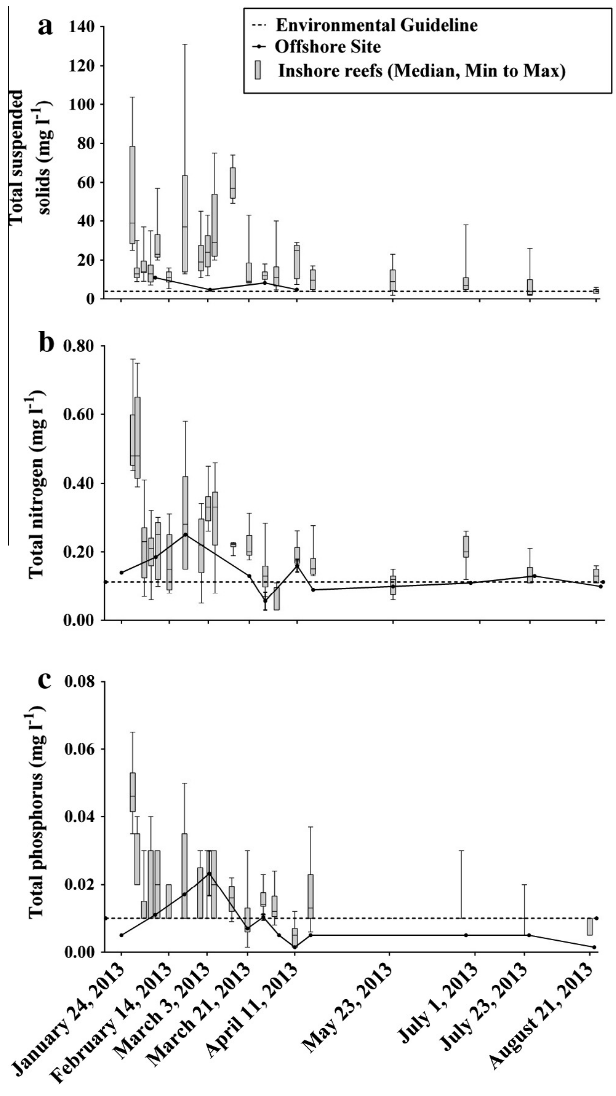

Fig. 6. Total suspended solids (a), total nitrogen (b) and total phosphorus (c) at nearshore reef water quality sites and at the offshore government water quality site in Hervey Bay, Queensland, Australia in comparison with local environmental guidelines (DERM, 2010a). Boxplots show medians, 25th and 75th percentiles, and minimum/maximum values. Offshore site data: ©State of Queensland (Department of Science, Information Technology, Innovation and the Arts) 2013.

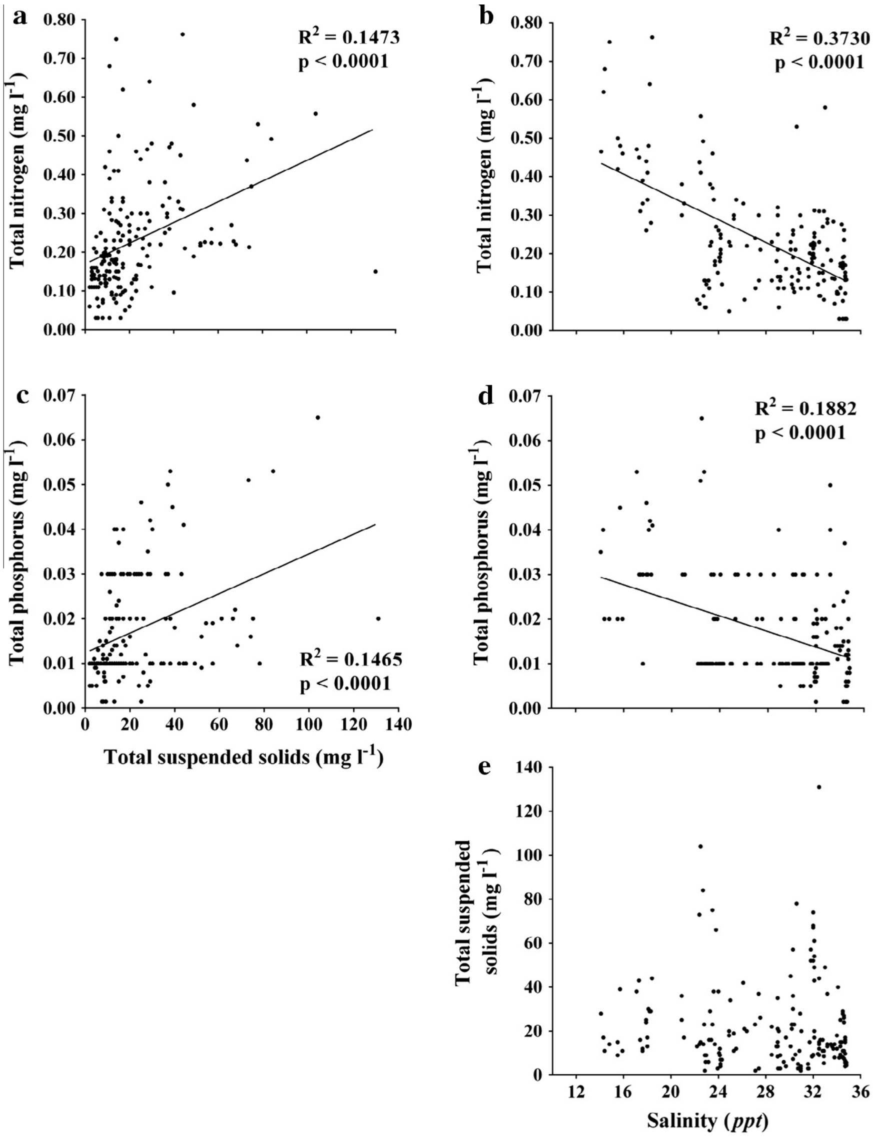

Fig. 7. Plots of: total nitrogen versus (a) total suspended solids and (b) salinity; total phosphorus versus (c) total suspended solids and (d) salinity, and; (e) total suspended solids versus salinity during the Mary River floods of 2013 in Hervey Bay, Queensland, Australia. Regressions included where significant.

dominant wind patterns and coriolis effect (Devlin and Brodie, 2005). It is also likely that there was considerable localised spatial variation in impacts as a result of: variable height of flood waters, variable flood plume direction and the local hydrodynamics during and immediately subsequent to the flooding. For instance, we observed variable turbidity at the different reef locations depending on the wind direction and strength and these same factors would have had similar influence on the transport of hypo-saline waters. Finally, sediment related stressors, such as wind driven resuspension, are likely to linger in Hervey Bay as a result of the accumulation of sediment and nutrients, which gradually disperse northward along the shore over time (BPA, 1989).

4.3. Reduced impacts of subsequent floods

The floods of January 2013 were some of the highest floods in the recorded history of the region, with the level of the Burnett River the highest ever recorded (9.53 m). Even so, at ~28%, overall coral mortality for Hervey Bay was reduced in comparison with that of the 2011 floods (~40%), in which flood height on the Mary was only marginally larger (8.2 m) than the single smaller flood in February 2013 (8.10 m) (BOM, 2013). The floods of 2011 occurred after a decade of severe drought conditions ("The Millennium Drought") (Cai et al., 2014) and, as a result, the flood likely contained higher levels of sediment and nutrients than if the flood had occurred soon after a prior flood. The comparison of water quality in 2011 and 2013 support this assertion in that 2011 had equal or greater sediment and nutrients and greater duration, despite being a single smaller flood. While salinity appears to have been higher in 2011, this is possibly a result of the monthly water quality measurements missing the sharp dip in salinity that was detected in 2013. It is also very likely that the higher mortality experienced in 2011 was a result of the high mortality of the more flood sensitive corals, which had grown well during the drought years but were decimated during the floods. The more flood resistant species, which made it through the 2011 floods, would also be more likely to persist through the 2013 floods. For example, at Pt. Vernon East, coral communities

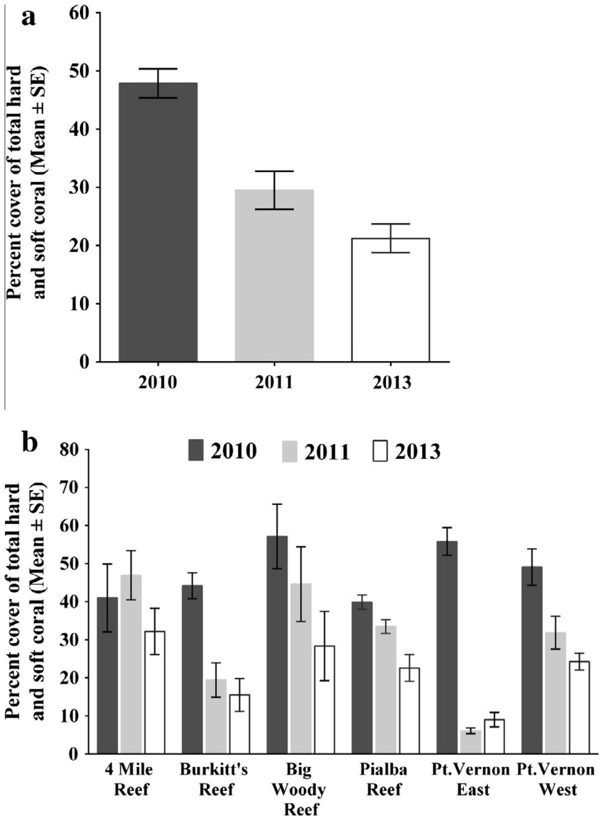

Fig. 8. Total abundance of hard and soft coral for overall reefs (a) and for each reef (b) in 2010, 2011 and 2013 in Hervey Bay, Queensland, Australia.

are now dominated by *Turbinaria mesenterina*, a coral known to be resistant to sediment and low salinity (Sofonia and Anthony, 2008; Faxneld et al., 2010). This reef suffered an ~89% decrease in coral abundance in 2011 but abundance increased from 2011 to 2013 (Fig. 8b).

4.4. Nearshore versus offshore water quality

The ongoing offshore water quality measurement program carried out by state government is a useful database for monitoring long term water quality conditions in GSS and Hervey Bay. It is not able, however, to capture the highly variable conditions during extreme events. Our study highlights the, at times enormous, discrepancy between nearshore and offshore conditions during flood plumes. At nearshore locations, water quality showed substantially greater deviation from environmental guidelines than at the offshore site. While the reduction in sampling frequency of the offshore program would have reduced the detection in temporal variability, overall, conditions in nearshore areas were more extreme, more variable and of longer duration. This is especially the case for TSS where nearshore processes such as wind and tides can lead to prolonged resuspension, turbidity and nutrient levels, which would not be detectable at offshore locations. The results from nearshore water quality monitoring therefore highlight the spatial variability of salinity, TSS, turbidity, nitrogen and phosphorus and that these parameters require consideration for any water quality monitoring programs, especially where the habitat of concern is situated inshore.

Table 3
Permutational analysis of variance (PERMANOVA) with distance covariates for changes in absolute cover between 2011 and 2013 for total (hard and soft) coral on the reefs of Hervey Bay, Queensland, Australia.

Source of variation	*df*	MS	Pseudo-*F*	*P*
Distance mainland	1	33.68	16.486	0.001
Distance river	1	18.33	8.9724	0.006
Distance mainland × distance river	1	1.5962	0.78132	ns
Flood	1	8.8364	4.3253	0.048
Distance mainland × flood	–	–	–	ns
Distance river × flood	–	–	–	ns
Error	60	2.043	–	–

ns = not significant ($P > 0.05$).

4.5. Submarine groundwater discharge

Submarine groundwater discharge (SGD) is a natural worldwide occurrence which can support important marine habitats, such as seagrasses (Johannes and Hearn, 1985; Rutkowski et al., 1999), but SGD can also hinder the presence of communities such as coral reefs (Moore, 2010), which are less tolerant of lower salinities (Berkelmans et al., 2012). The twenty week post-flood hyposaline conditions observed following the 2013 flood events were most likely a result of delayed SGD. This exposure period, though of higher salinity than during the flood plumes themselves, was of more than double the duration of the actual flood plume and was sustained for the entire period, rather than episodic as was the case for the hypo-salinity from flooding. In addition, whereas the hypo-saline conditions of floodwaters were concentrated near the surface, the impacts from SGD differ in that the source of water may arise from below the substrate and potentially impact benthic

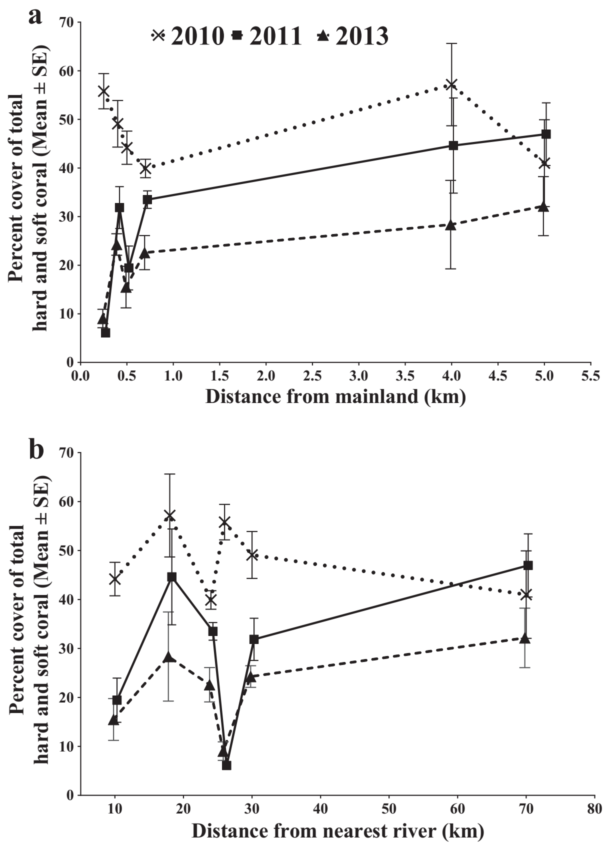

Fig. 9. Total abundance of total hard and soft coral on six reefs from Hervey Bay, Queensland, Australia in 2010, 2011 and 2013: (a) relative to distance from mainland; (b) distance from nearest river.

Table 4
Permutational analysis of variance (PERMANOVA) with distance covariates for changes in absolute cover after repeated flooding (2010–2013) for total (hard and soft) coral on the reefs of Hervey Bay, Queensland, Australia.

Source of variation	*df*	MS	Pseudo-*F*	*P*
Distance mainland	1	5.4816	4.0642	ns
Distance river	1	0.93721	0.69487	ns
Distance mainland × distance river	1	0.8052	0.59699	ns
Flood	1	95.275	70.639	0.001
Distance mainland × flood	–	–	–	ns
Distance river × flood	1	7.0607	5.235	0.022
Error	55	1.3488	–	–

ns = not significant ($P > 0.05$).

organisms at depths greater than would have been affected by floodwaters alone (Kotwicki et al., 2014).

There are many possibilities for the source of the Hervey Bay SGD. While local coastal sandy areas and the local abundance of groundwater dependent habitats (BOM, 2015) suggests the possibility of a local source within kilometres from the bay, the vertically upturned, coal seam bearing sub-tidal bedrock, which is characteristic of this area (Stephens, 1971) indicate a geological connection with areas much further inland and the possibility of far more distant sources of the groundwater. The weeks of delay between flooding and SGD outflow could have been caused by water being transported long distances; by water travelling slowly (Johannes, 1980) or by time needed for pressure to build up to outflow release (Gonneea et al., 2013).

From a catchment management perspective, this SGD should be further investigated to monitor the quality of the water transported to marine habitats. Where SGDs are contaminated with nutrients and/or pollution, as exemplified by occurrences in Brazil (Costa et al., 2008) or in the Philippines (Senal et al., 2011), the outflows can adversely affect adjacent marine habitats. Fortunately, SGD in Hervey Bay seems to have only altered salinity, as elevated nutrients and suspended solids were not evident in the nearshore waters. While its source remains unknown, great care should be taken to minimise contamination of any possible recharge areas, which may include urban, agricultural or mining areas inland from Hervey Bay. If the groundwater is being transported great distances, it may take decades or even centuries (Johannes, 1980) before the legacy of any recent contamination becomes apparent in the discharge into Hervey Bay waters.

4.6. Recovery

For a coral reef to persist, adequate recovery periods between disturbances are necessary to facilitate the return of health, to enable growth and to allow for the recruitment of new corals to the reefs (Karlson, 1999; Graham et al., 2011; Johns et al., 2014). The waters of Hervey Bay are affected by floodwaters from the Mary River on average every few years (BOM, 2014), but with occasional longer gaps, such as the decade long decrease in rainfall and flooding just prior to the 2010 flood event. In recent years, water quality has remained poor, which has been attributed to a combination of catchment modification and flooding (Reefplan, 2014). Should rainfall and flooding continue at rates observed from 2010 to 2013, Hervey Bay coral abundance and coral diversity are likely to continue to decline such that only the most flood resistant of corals can persist. The summer periods from 2010 to 2012 had one of the highest Southern Oscillation Indices (SOI) (La Niña episode) on record for Australia (BOM, 2012) and it is expected that conditions will soon revert back into drier, lower SOI periods (El Niño). Although El Niño periods are generally associated with higher sea temperatures and therefore increased likelihood of coral bleaching, El Niño periods also tend to lead to a reduction of rainfall and therefore reduced terrestrial runoff. This is likely to assist the recovery of Hervey Bay reefs as less freshwater, sediments and nutrients are transported to Hervey Bay and lingering sediment and nutrients from past floods are dispersed north out of the bay. It is thus plausible that prolonged dry periods increase recovery potential of corals in Hervey Bay.

4.7. Conclusion

Substantial effort is being made world-wide to understand terrestrial runoff and water quality at large spatial scales (e.g. across thousands of kilometres). While this is a very important endeavour, our local scale study highlights how fine-scale monitoring (e.g. tens of kilometres), can help understand the cumulative, highly variable and extreme conditions of flood plumes and their impacts on the marine environment. Our study shows that fine-scale water quality monitoring can reveal surprising information, such as SGD, which cannot easily be detected by satellite imagery and large scale monitoring. High-latitude coral reefs, such as those of Hervey Bay, exist in conditions considered marginal for coral reef growth in terms of reduced temperatures, sunlight and aragonite (Guinotte et al., 2003). The persistence of these marginal coral reefs will therefore likely benefit from improved catchment management and the minimisation of transport of hypo-saline waters, sediment and nutrients (Wooldridge and Done, 2009). Our study illustrates that local-scale water quality monitoring can inform local scale management and conservation, such as that needed for marine park zoning or catchment management.

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